



Compaction of Forest Soils

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Logging and other mechanized forestry activities often lead to soil compaction, which can reduce seedling and residual tree growth and promote surface erosion. The extent of these impacts is largely a function of the initial soil characteristics, the amount and type of forces applied, and the resulting area and depth of compacted soil.

The land manager must balance the expected effects and related costs of compaction with economical techniques for minimizing the problem and improving the situation. Among the most promising methods for accomplishing this are the use of designated skid trail systems and soil tillage.

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COMPACTION OF FOREST SOILS

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As with food crop production in the last few decades, timber production in recent years has become increasingly dependent on mechanized equipment. Many common forest management practices, from site preparation to harvest, now involve some type of heavy machinery. Mechanization typically improves the time- and cost-efficiency of these forest operations. The use of machinery on the forest site, however, can significantly alter some important soil properties and produce both onsite and offsite impacts on forest and related resources.

Soil compaction is one commonly observed consequence of the use of machinery on forest sites. The negative impacts of soil compaction on these sites include the reduced growth of seedlings and residual trees and, in some cases, increases in surface runoff and erosion. Forest practices and site conditions are extremely variable, however. These impacts do not always occur, nor are the impacts equal when they do occur. Further, when the potential for soil compaction exists, certain management practices can be used to prevent or reduce the associated impacts.

In the following discussion we will describe more fully the nature, effects, and variability of forest soil compaction. We will also describe how soil compaction is recognized and measured, and we will discuss management alternatives for reducing compaction problems.

The Nature of Soil Compaction

A productive forest soil is typically a mixture of mineral particles, plant and animal matter, air, water, and associated nutrient elements. Less than half of a given volume of soil in a physical condition favorable for most plants is solid material, with the rest being pore space containing varying amounts of air and water (figure 1). Soil pore space originates from a number of important sources. Much of it results simply from the tiny cracks and crevices that are found naturally between individual soil particles and between aggregates of soil particles. Additional pore space results from channels left by earthworms, burrowing animals, decaying plant roots, and the freeze-thaw and wet-dry cycles of the soil.

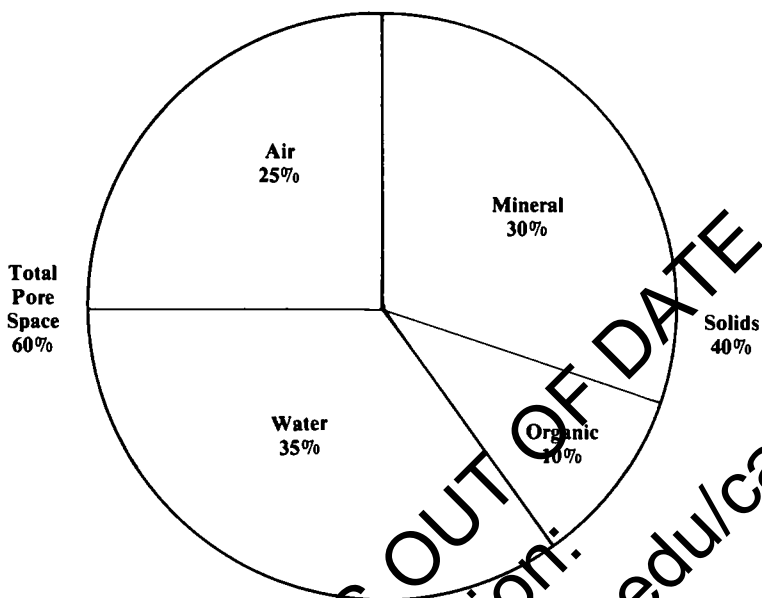


Figure 1. Typical distribution of major physical components (percent of total bulk volume) in the surface mineral horizon of a productive Coast Range forest soil.

A compacted soil shows an increased bulk density (dry soil weight per unit volume, usually expressed in grams per cubic centimeter of soil) as a result of applied loads, vibration, or pressure (figure 2). These compactive forces acting upon the soil can originate from many sources, from foot traffic to the ground pressure under the wheels or tracks of heavy machinery. Since the individual soil mineral particles are generally rigid and resistant to changes in density, compaction usually occurs at the expense of soil pore space. Typically, an applied force pushes together the particles and aggregates of soil, effectively filling or compressing many of the existing soil pores. The pores most easily affected in this way are the larger channels or macropores (figure 3), through which air and water movement is normally unrestricted and rapid, and which generally provide a good environment for root growth. These qualities can be changed when compaction reduces this large pore space, leading to many of the problems commonly linked to soil compaction.

The degree of compaction that occurs in any given area is influenced by several factors related to the soil and the forces applied to it. Among the most important are the amount and type of pressure and vibration applied, the depth and nature of the surface litter, the soil texture (the dominant size classes of mineral particles) and structure (the nature of the clods of individual particles), and the soil moisture level during compaction.

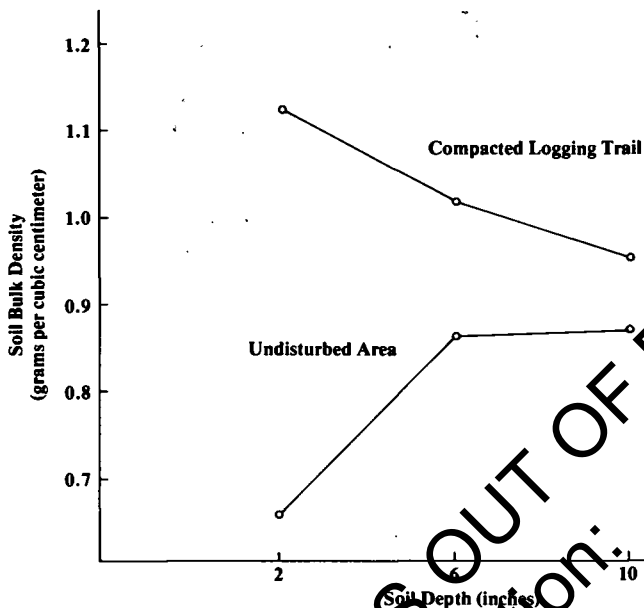


Figure 2. Soil bulk densities in adjacent logging trail and undisturbed area on the Mount Hood National Forest.

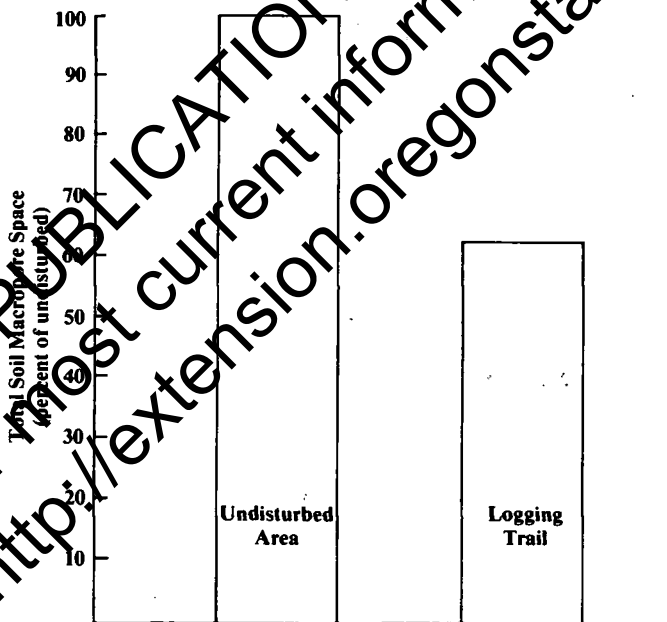


Figure 3. Total soil macropore space in an adjacent logging trail and undisturbed area in northern California

Estimates of standing ground pressure created by a person, horse, and several types of logging machinery show a wide range of values (figure 4). The relatively high values for people and livestock are the result of their weight being concentrated on a small area under the feet or hooves. But standing ground pressure does not necessarily indicate the degree of compaction that can be expected. Differences in vibration, dynamic pressures during loaded movement or turning, or the total ground area affected can produce relative compaction levels that do not correspond to the differences in standing ground pressure between animals or equipment types.

Another important equipment-related factor that influences the degree of soil compaction that occurs is the number of trips made over a given area of ground. Generally the greatest density changes occur during the first few equipment passes, with progressively smaller increases thereafter (figure 5). Site characteristics and the capacity and design of the machinery used will normally dictate the number of equipment passes necessary to accomplish any specific task.

When similar compactive forces are applied to different soils, the observed density increases are closely related to the initial physical properties of the soils. Less compaction typically occurs, for example, in soils with strongly developed structure and high strength characteristics. Some resistance to soil compaction is similarly found where thick layers of surface litter provide cushioning against compactive forces. Varying soil water contents provide cohesion, lubrication, or buoyancy to adjacent soil particles and aggregates. Compaction can thus be enhanced or inhibited at certain moisture levels. The soil moisture levels associated with maximum or minimum compactibility, however, vary considerably with other soil characteristics and the compactive forces applied.

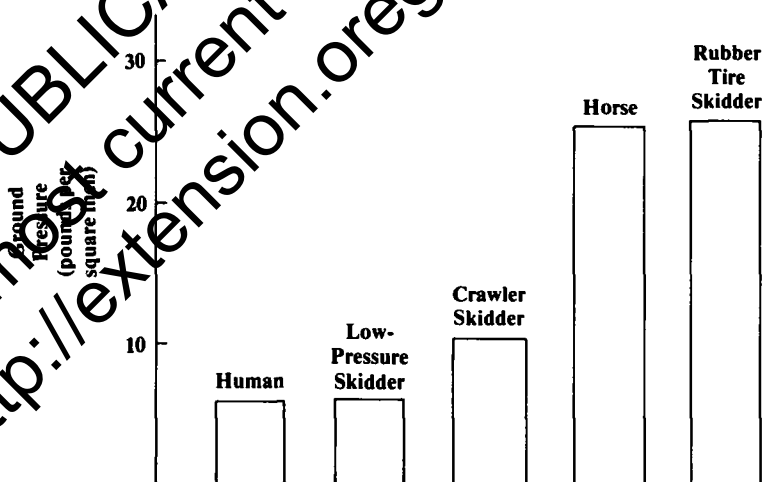


Figure 4. Approximate standing ground pressure of a person, horse, and several types of machinery.

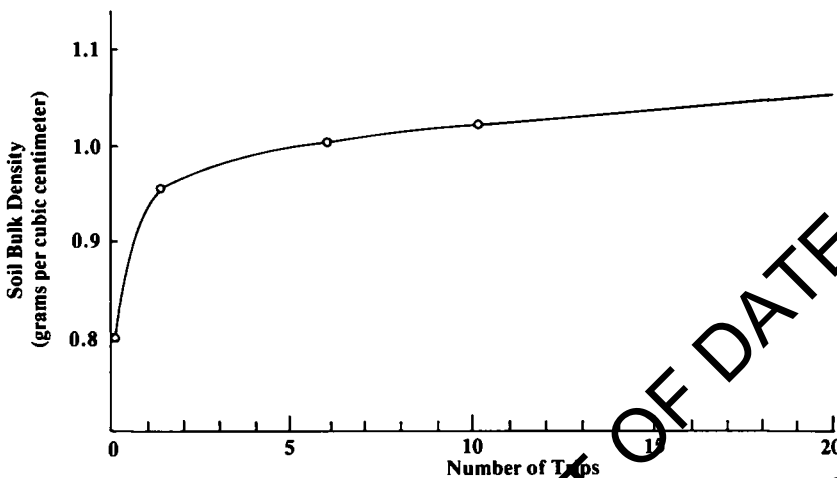


Figure 5. Effect of number of passes of logging equipment on soil bulk density in study area on the Mount Hood National Forest (average for a 10 inch soil depth).

Soil compaction can persist for decades, or it can be significantly reduced within a few years under favorable conditions. Soils with very active plant roots, soil organisms, or regular freeze-thaw and wet-dry cycles are most likely to quickly recover from compaction. Coarse-textured soils with relatively weak soil structure also tend to recover more quickly than fine-textured soils. Unfortunately, the moderate climate and particular soil types common to the Pacific Northwest seem to produce some very slow rates of recovery from compaction.

The Effects of Soil Compaction

One of the greatest concerns of land managers is the potential for reduced soil productivity in compacted areas. Many studies have shown that compacted soils often have characteristics that are generally considered unfavorable for plant growth. These characteristics include high bulk density and reduced porosity, aeration, and drainage. Root penetration and growth is often decreased in soils of high density, since the relatively high strength of these soils offers physical resistance to expanding root systems. Supplies of air, water, and nutrients that roots need can also be unfavorably changed when compaction decreases soil porosity and drainage. In lowland areas, water can collect on and near the surface of slow draining compacted soils, further reducing air movement to roots.

Measurements of reduced tree and seedling growth on compacted soils show that significant impacts can and do occur. Seedling height growth has been most often studied, with reported growth reductions on compacted soils from throughout the U.S. ranging from about 5 to 50 per cent. In studies of

residual tree growth in thinned stands in the Pacific Northwest, overall volume growth response in stands with compacted soil was reduced by 5 to 15 per cent. Individual trees, however, showed growth impacts that ranged from 0 to about 40 per cent. Similar growth impacts have been observed for commercial-sized trees in unthinned stands established on compacted soil.

Soil compaction can clearly reduce the growth of seedlings and trees, but the many factors that influence compaction and its resulting impacts make the estimation of expected growth losses on any given compacted area a complex problem. For example, seedling height growth losses apparently vary with the amount of increase in soil density following compaction (figure 6). As indicated earlier, the increase in soil density that occurs in an area depends upon a number of important soil, site, and equipment characteristics.

Other important soil and site conditions that affect the degree of growth impact resulting from compaction include the depth of the compacted layer, the area of tree or seedling roots affected by compaction, and the natural rate of recovery of the soil from the compacted condition. For example, the deeper the extent of compacted soil and affected rooting zone, the greater and longer will be the growth impact.

Compaction depth is often quite variable both within and between different sites, but the most severe compaction is usually found within a few inches of the soil surface (figure 2). Compaction below this level normally decreases with depth, and it is generally negligible beyond 18 inches. Most of the fine nutrient- and water-absorbing tree roots are found in the surface soil layers where compaction usually occurs.

Since tree roots extend not only in depth but also in area, the potential for growth impact also becomes greater as compaction affects more of the rooting area. In a thinned stand, for example, you can expect the greatest

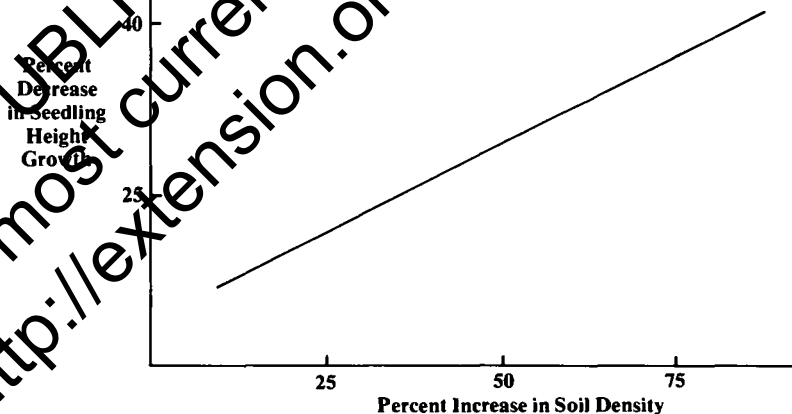


Figure 6. Relationship between increases in forest soil bulk density and the height growth of tree seedlings (based on field studies of a variety of tree species, soil types, and locations).

growth impacts in residual trees that closely border major skid trails or that have been subject to traffic on more than one side of the stem. The natural rate of recovery of a compacted soil will also determine whether related growth impacts are to be short-lived or persistent. Long term impacts are likely for many forest soils in the Pacific Northwest, since it was earlier indicated that slow recovery from compaction seems to be common here.

Besides the significant effects of soil compaction on tree and seedling growth, compaction also bears some important relationships to surface runoff and erosion that can also be of concern. Reduced infiltration and drainage from compaction, for example, can lead to surface runoff when rainfall intensities exceed the infiltration capacity of the soil. This runoff can concentrate in or near existing roads, adding to the stresses already placed upon the drainage systems designed for those roads. If compaction is extensive, increased surface runoff may also increase storm flows in small headwater streams, raising the potential for such problems as channel scour.

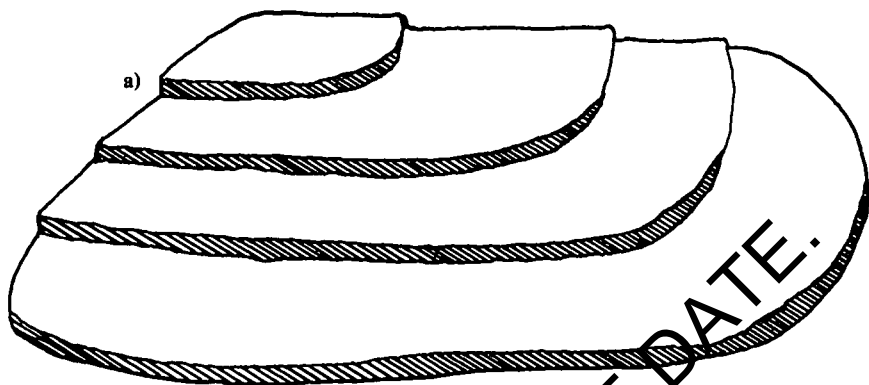
Soil erosion can also result when surface runoff becomes heavy and rapid enough to carry away soil particles. Erosion can decrease site productivity from the loss of fertile surface soil, and the sediment produced can damage fish habitat and general water quality. The problems caused by erosion and the relationships between erosion and compaction on forest land are discussed in greater detail in another Pacific Northwest Extension Publication, *Impacts on Forest Practices on Surface Erosion* (PNW 195, Jan. 1980).

Recognizing and Measuring Soil Compaction

Heavily compacted soils can often be readily recognized in the field. These soils are usually difficult to penetrate and excavate with a shovel or spade, particularly when they are dry. Engineers have long recognized that compaction increases soil strength; they intentionally compact road subgrades and building foundations for increased stability. The individual clods excavated from a compacted soil are often large and difficult to break up. When the clods are broken up, however, they often fracture into flat, platy pieces that are oriented parallel to the soil surface. This platy soil structure is quite different from the granular or crumb structure commonly found near the surface of many forest soils (figure 7). Altered structure and reduced drainage in compacted soils can also lead to the appearance of surface runoff or the presence of standing water, even during periods of relatively dry weather.

The bare mineral soil often found in compacted areas such as skid trails can be a good site for seed germination. Young plants and tree seedlings are abundant in many of these areas as a result, but compaction often inhibits further plant development. Therefore, another potential indicator of severe compaction is the presence of stunted plants or tree seedlings.

While general field observations can be useful in recognizing severe compaction problems, measurement of actual changes in soil density permits the detection of less obvious levels of compaction. This also gives a better indication of some of the potential impacts of compaction, since the



Platy Soil Structure



Figure 7. a) Platy structure often found in compacted soils. b) Granular structure typical of the surface mineral horizon of productive forest soils.

measurements can be applied to a relationship like that shown in figure 6. Cores of relatively undisturbed soil have been most often used to measure soil density and compaction. Knowing the volume of each collected core sample, you can calculate the soil bulk densities after drying and weighing the cores.

In recent years the nuclear densimeter has also been frequently used to evaluate soil density and compaction. This device is based on the principle that as a material becomes increasingly dense, the ability for radioactivity to travel through it will decrease. Major advantages of this type of equipment are that the measurements average a relatively large volume of soil and can be taken directly in the field without removing any soil.

Since compaction often alters soil physical properties in addition to bulk density, other measurements can be made to detect compaction and to evaluate possible related impacts. For example, changes in drainage can be

determined with infiltration measurements in the field or in the laboratory with collected soil cores. This procedure involves the application of known amounts of water to the surface of the soil or soil cores and measurement of the time needed for the water to move into the soil.

A device called an air permeameter can be similarly used to measure the resistance of the soil to air movement. The increased soil strength that usually accompanies soil density increases can be determined in various ways to also provide an index of compaction. Probably the simplest device to use is the hand-held soil penetrometer, which measures the amount of force needed to penetrate the soil with a standard probe.

You can take penetrometer measurements quickly and easily, which makes it particularly effective for large or multiple surveys. However, penetrometer readings need to be calibrated for different soil types and moisture levels to provide useful information.

Considerations for Management

The problem of forest soil compaction presents two formidable tasks for the land manager, estimating the impacts and related costs of specific forest operations and determining effective and economical techniques for minimizing these impacts and costs. There is currently no widely accepted procedure for accomplishing these tasks, but careful study of available management alternatives and information like that given in the previous sections should generate some useful approaches.

Several management alternatives exist for minimizing the impacts of forest soil compaction. One approach for reducing compaction problems resulting from timber harvesting has been to replace ground-based operations with skyline or even helicopter systems. Soil impacts are usually minor with these systems, but on gently sloping terrain the costs of cable or aerial logging can be more than twice that of ground skidding. As a result, most forest managers are attempting to minimize compaction while continuing the use of ground-based systems.

Some land managers have used soil moisture information to control compaction by restricting ground-based equipment operations to periods of "favorable" moisture levels. This approach developed from observations in road engineering that showed that intentional compaction with specially designed machinery is most effective at a specific moisture content that is characteristic to each soil.

The basic idea behind this approach is reasonable, but its practical application in forestry presents a number of important problems. For example, the optimum moisture content for compaction shifts with different loads on the soil, so the soil reacts differently to compaction machinery compared to equipment commonly used in forestry. Thus the observations and guidelines in road engineering cannot be directly applied to forest operations. This has been verified in recent studies that show poor relationships between the results of the laboratory test commonly used to establish moisture restrictions in forestry (Standard Proctor Engineering Test) and the actual compaction resulting from the use of logging equipment.

Relationships between soil moisture and the compaction caused by forestry equipment will probably become better understood, but other problems exist in the use of moisture-based restrictions. One major difficulty is the prevailing variety of soil and equipment characteristics, which generally requires each soil type and operation to be evaluated independently. Soil moisture content is also often highly variable on any given site, presenting problems related to the procedures and equipment used to measure moisture and apply moisture-based restrictions. Another difficulty is that these restrictions can severely limit the operability of sites with soils that remain at high moisture levels throughout the year. In such cases excessive costs can result from delayed or eliminated forestry operations.

A more promising approach to soil protection during ground-based logging is the use of a designated skid trail system to limit the area of compacted soil. This technique can restrict compaction to 10 per cent or less of the land area, which is considerably lower than the 20- to 35- per cent total area normally found following conventional logging operations. Additional benefits are possible when permanent trails are established in a managed forest, since repeated equipment entries will not increase the area in skid trails. The use of designated trails during thinning operations in young conifer stands has been shown to be economical and efficient if the trees are felled to the lead of evenly spaced trails, and the logs are winched to the skidder (figures 8 and 9). Topography, equipment, and stand conditions will affect the design and suitability of designated trail systems, but in many situations this method should produce major benefits through the significant reduction in compacted area.

Another closely related management approach for reducing compaction problems that result from timber harvesting is to establish in the logging contract a percentage limit for the area that can be covered by skid trails. This obviously encourages planned skid trail systems and the use of techniques such as log winching, but it provides the flexibility that may be needed to deal with a wide range of logging and operator situations. Area percentage limits have been successfully used for several years as a tool for managing compaction problems in Oregon Mt. Hood National Forest.

Since heavy machinery produces forces that cause soil compaction, modifications in equipment design may help reduce compaction problems. For example, low ground-pressure, torsion-suspension logging vehicles have recently become available, and some land managers have recommended or required their use to minimize compaction. Unfortunately, little research has yet been done to compare the compaction and related impacts caused by low-pressure and by conventional logging vehicles. Results of the few available studies show that the low-pressure vehicles produce somewhat less compaction than conventional harvesting equipment, but it remains to be seen whether these differences are large enough to produce significant contrasts in tree growth and other specific site impacts.

The alternatives for minimizing soil compaction problems that have been covered thus far are generally preventative measures. Where the soil has

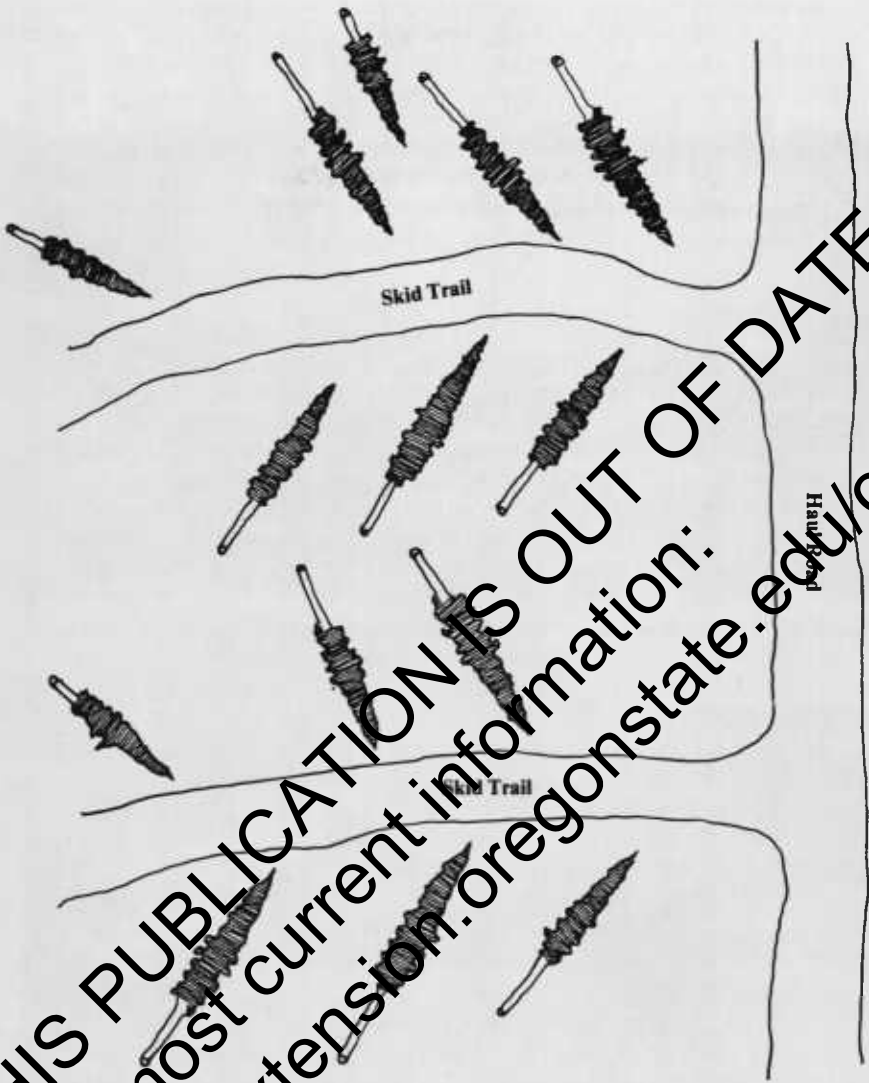


Figure 8. Designated skid trail system with trees felled toward the lead of the trails.

already been compacted, soil tillage can be used to alleviate the compacted condition. This practice has been successfully applied on agricultural lands for many years, and it is possible that similar results can be achieved from properly applied tillage of compacted forest soils (figure 10).

Some organizations are already requiring that ground-based forestry operations be followed by the tillage of vehicle trails. The costs of these

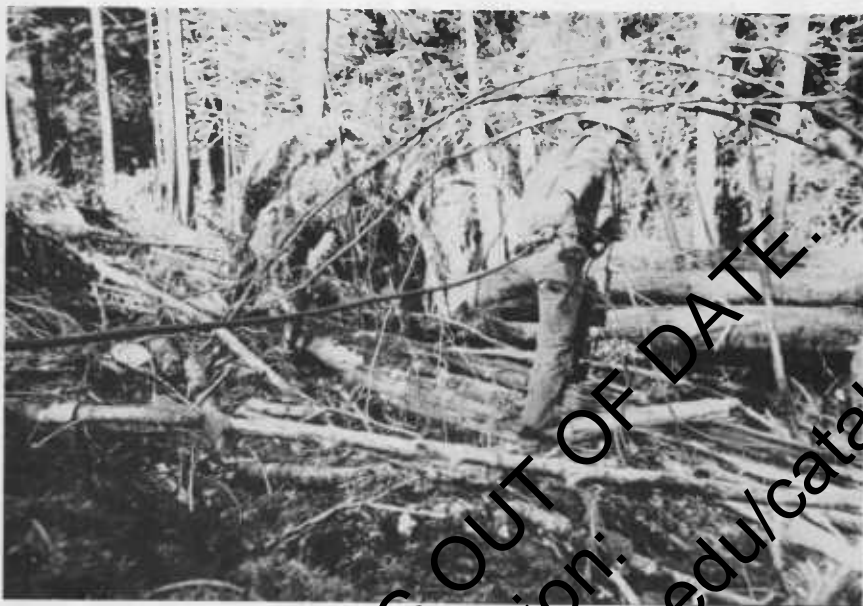


Figure 9. Line-pulling and winching of logs can be used to minimize equipment travel.



Figure 10. Tillage of major skid trails following logging operations can help alleviate compaction problems.



Figure 11. Brush blades are commonly used for tillage of compacted soils, but their effectiveness needs to be studied.

treatments can be quite reasonable, especially when the vehicles used in the original operations are used in the tillage treatments (figure 11). More research is needed, however, to determine whether tillage with conventional rock ripper teeth or brush rakes is an effective technique for restoring compacted soils.

No universal approach to minimizing compaction problems can be equally effective and economical for the many soil, site, and forest conditions encountered. Ideally, soil and silvicultural specialists should examine each unique set of conditions to determine the relative likelihood and expected impacts of compaction.

Land managers and operations engineers can then apply appropriate economic information to determine whether preventative or restorative measures are warranted and, if so, which measures are most suitable. This approach should lead to the establishment of effective and well-defined guidelines for our managed forest lands.

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